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# **Hydraulic Tidal and Wind Power System Sizing**

**Final Report**

*Jack A. Jones*

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The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

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# 1. Executive Summary

Tidal energy, offshore wind energy, and onshore wind energy can be converted to electricity at a central ground location by converting their respective energies into high-pressure hydraulic flows that are transmitted to a system of hydraulic generators by high-pressure pipelines. The high-pressure flows are then efficiently converted to electricity by a central hydraulic power plant, and the low-pressure outlet flow is returned. All gears and submerged electronics are completely eliminated (JPL/Caltech patents granted and pending). The Department of Energy (DOE) is presently supporting a project led by Sunlight Photonics to demonstrate a 15 kW tidal hydraulic power generation system in the laboratory. Sunlight Photonics will issue a separate report on this experimental phase, which has successfully integrated and demonstrated all major hardware components.

Another portion of this DOE project involves sizing and costing a 15 MW commercial tidal energy plant, which is the subject of this Final Report. For this task, Atlantis Resources Corporation's demonstrated 18-m diameter tidal blades operate in a nominal 2.6 m/sec tidal flow to produce one MW per set of tidal blades. Fifteen blade units are submerged in a deep tidal area, such as Maine's Western Passage. Each set of blades is attached to commercial-off-the-shelf (COTS) Hagglund radial piston pumps, and all pumps are connected to a high-pressure (20 MPa, 2900 psi) line that is 35 cm ID. High-pressure HEPG fluid is transported 500 meters to a parallel series of onshore, COTS axial piston hydraulic generators. HEPG is an environmentally-friendly, biodegradable, water-miscible fluid. The total cost of producing energy with this tidal power plant is estimated to be \$0.15/kW-hr, which is between the cost of wind energy and solar energy.

Hydraulic adaptations to Ocean Renewable Power Company's (ORPC's) cross-flow tidal turbines are also discussed. Costs to convert a submerged ORPC tidal system to a hydraulic device with onshore power generation are about 50 cents per watt, minus the cost of ORPC's expensive submerged generators, which would be entirely removed.

Although not originally planned, applications of Hydraulic Energy Transfer (HET) for wind energy have also been added to this report. For wind energy that is onshore or offshore, a gearless, high-efficiency, COTS, radial piston pump can replace each set of troublesome, top-mounted gear-generators for conventional wind turbine systems. Environmentally friendly HEPG fluid is then pumped to a central system of easily serviceable ground generators, which consist of a parallel series of axial piston hydraulic generators. Total hydraulic/electrical efficiency of 81% is close to that of conventional wind turbines at full-rated wind speeds. Total HET efficiencies increase at slower speeds, however, while conventional wind turbine efficiencies decrease significantly. In addition, all troublesome gears are eliminated for HET wind and tidal energy systems.

## 2. Introduction: State of the Art for Tidal and Wind Energy

There are numerous ways to obtain non-carbon-emitting, renewable electrical power. One of the objectives of this paper is to briefly review some of the state-of-the-art for tidal energy and wind energy systems. A new hydraulic energy transfer (HET) design will be discussed that allows centralized, ground-based power generation for onshore and offshore wind energy, as well as for tidal and river current energy.

### 2.1 Tidal Energy

There are many different types of tidal power technologies. A partial list of categories includes the following (Reference 1).

**Barrage or dam:** A barrage or dam is typically used to convert tidal energy into electricity by forcing the water through turbines, activating a generator. Gates and turbines are installed along the dam. When the tides produce adequate difference in the level of water on opposite sides of the dam, the gates are opened. The water then flows through the turbines. The turbines turn an electric generator to produce electricity. Small power plants using this technology are now functioning in France, Russia, and Canada. The dams have been criticized, however, for resulting in the accumulation of silt and other material behind the dams.

**Tidal Fence:** Tidal fences look like giant turnstiles. They can reach across channels between small islands or across straits between the mainland and island. The turnstiles spin via tidal currents typical of coastal waters. Some of these currents are 5-8 knots and generate as much energy as winds of much larger velocity. Tidal fences also impede boat traffic, as well as sea life migration.

**Horizontal Axis Tidal Turbines:** There are many types of horizontal axis tidal turbines. The most common of these tidal turbines look like wind turbines. They are arrayed underwater in rows, as in some wind farms. The turbines function best where coastal currents run at between 3.6 and 4.9 knots: In currents of that speed, a 15-m diameter tidal turbine can generate as much energy as a 60-m diameter wind turbine. Ideal locations for tidal turbine farms are close to shore in water depths of 20 to 30 meters. This type of tidal turbine generally does not impede sea life migration or result in silt buildup.

The first tidal generator actually attached to a commercial grid in the United States was operated by Verdant Power in New York City's East River. Verdant's Roosevelt Island Tidal Energy (RITE) Project was initiated in 2002 and was operating on-grid intermittently until 2009. The project consisted of six 35-kW horizontal axis turbines that were fully bidirectional and accumulated over 7000 hours of operation. A simple operational schematic of a horizontal blade tidal turbine system is shown in Figure 1. The tidal flow turns a blade at about 15 rpm, which is increased to about 1500 rpm by means of a gearbox. The higher rpm is then used to generate electricity by means of a submerged generator, and the energy is sent to shore with submerged power lines. The project was plagued by a number of problems, including blades breaking off and salt water leakage into the generators. Reinforced turbines

were installed in September 2008 (Reference 2), but they all eventually failed due to salt-water leakage into the submerged generators. Verdant has recently received a license to attempt to reinstall 30 generators by 2015.

Atlantis Resources Corporation, which is a partner in this DOE-sponsored task, has an 18-m diameter tri-blade system (Figure 2) called AR-1000. It is a powerful and efficient single-rotor turbine expressly designed for offshore ocean use. The AR-1000 combines a fixed pitch blade operation, a single stage gearbox, and a flexible coupling to the highly efficient permanent magnet generator with a rating of 1.0MW at 2.65m/s. The complete tidal turbine system is fully UK-grid-compliant, employing features developed over the past 10 years.

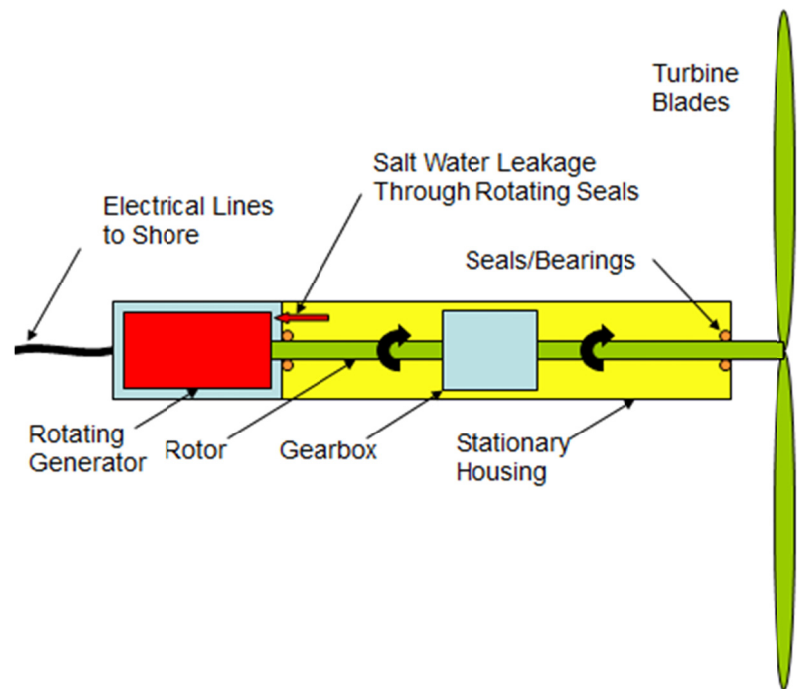


Figure 1. Typical Horizontal Axis Submerged Tidal Turbine



Figure 2. Atlantis Resource Corporation's 18-m Tidal Turbine

The AR-1000 was first connected and generated to grid in June 2011. This was achieved at the EMEC test facility using the same existing gravity-based structure and connection platform developed for the revision generation AK-1000 turbine deployed in 2010. Testing has proved that the water-to-wire efficiency of the device is in excess of 42%, as predicted by theoretical modeling. Testing of the system to refine the control system and improve the overall system reliability is still ongoing.

There are numerous other versions of horizontal axis turbines, including Marine Current Turbines, which use counter-rotating blades on a common tower (Figure 3) This design became the world's first operational in-stream tidal turbine in 2008, generating 1.2 MW on Strangford Lough in Northern Ireland.

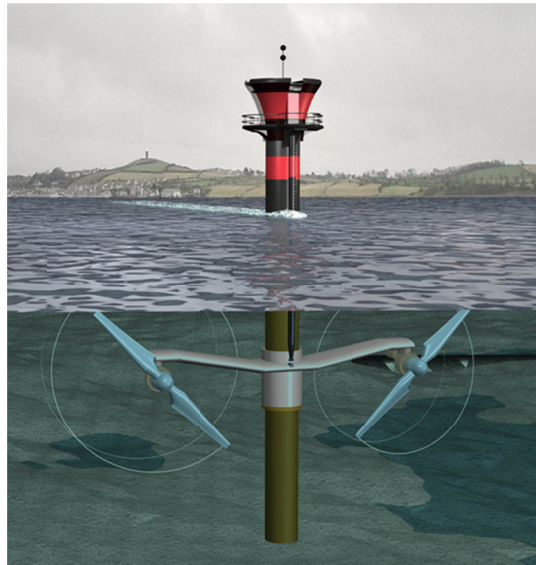


Figure 3. Marine Current Turbine Arrays

Ocean Renewable Power Company (ORPC) produces an alternative type of in-stream tidal generation system, which uses unique cross-flow turbines that drive a permanent magnet generator on a single shaft (Figure 4). These units can be stacked vertically and horizontally into much larger units. A 4x4 unit can produce about 763 kW in a 2.6m/sec tidal flow. The units use a permanent magnet generator and do not require a gearbox. Also, they turn in the same direction regardless of incoming or outgoing tide.

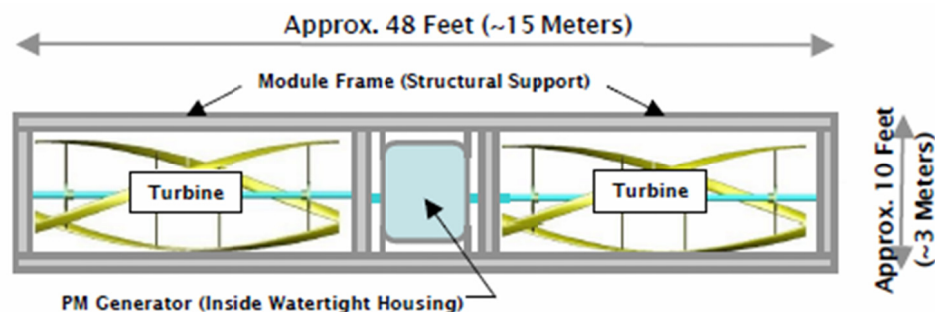


Figure 4. ORPC Cross-Flow Tidal Generator

## 2.2 Conventional Wind Turbine Systems

Wind turbines have been used to generate electricity since the late 19th century, although the modern wind power industry did not begin until about 1979, when several European countries began commercially producing small wind turbines. Worldwide, wind power now has the capacity to generate 430 TWh annually, which is about 2.5% of worldwide electricity usage (Reference 3-4). In terms of potential wind generating power, as stated by DOE, offshore wind energy could potentially supply 4,000 TWh/yr in the US alone, and onshore wind energy could potentially supply an additional 37,000 TWh/yr (Reference 5). This total potential U.S. wind energy production is about ten times more than the entire 2010 U.S. electricity demand of about 4,000 TWh/yr (Reference 6). Wind energy costs are significantly lower than natural gas, solar power, or coal with carbon sequestration (Reference 7).

The operating theory behind most present wind turbines is shown by the schematic drawing in Figure 5. Typically, three blades are used to harness the wind and transfer their slow-revolving torque to a gearbox. The gearbox increases the rpm to about 1800 rpm, and the attached alternator then generates electricity. At high wind speeds, total efficiency is close to about 80% of theoretical values, but this drops greatly at slower wind speeds. Not only does the total available power drop off according to the cube of velocity, but the relative efficiency of the gearbox and alternator greatly decrease with wind speed.

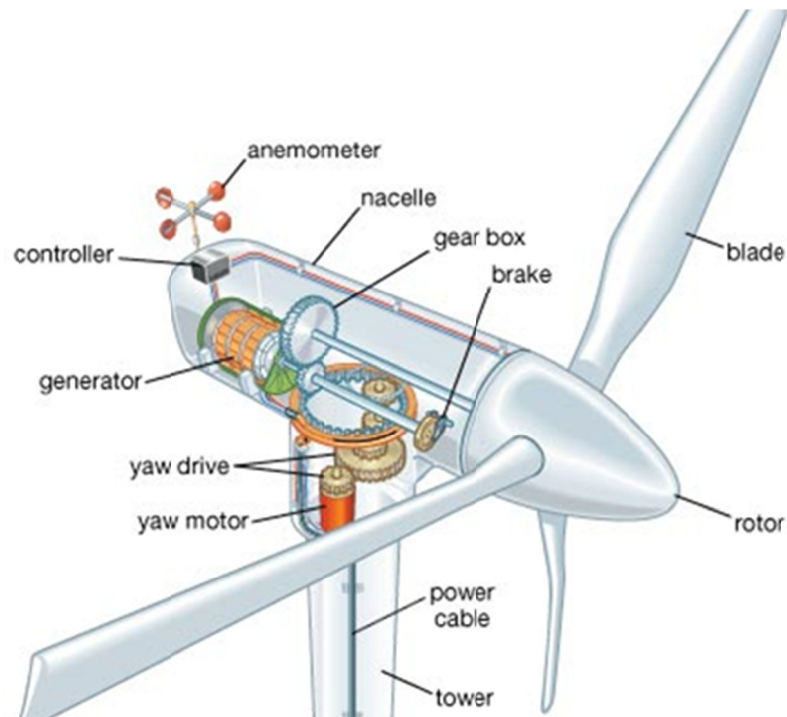


Figure 5. Typical Wind Turbine Components

The gearboxes are the primary failure mode for wind turbines, and servicing the generator or gearbox at the top of the wind mast is their primary maintenance cost. Three European companies (Chap Drive/**Norway**, Artemis/**Scotland**, and Voith Turbo WinDrive/**Germany**) have replaced the top-mounted wind turbine gears and generator with a top-mount hydraulic



pump. The hydraulic pump then sends oil to a hydraulic generator at the bottom of the mast. The two big advantages to this type of design are that the gearbox is completely removed, and maintenance on the ground-level generator is greatly facilitated.

Delft University in the Netherlands has taken hydraulic wind power generation one step further for offshore wind power generation. They use a hydraulic oil loop on the mast to power a seawater pump that sends high-pressure seawater to a generator on a remote platform (Figure 6). Electricity from hydroelectric generators is then transferred to shore by means of a buried cable (Reference 8). Total electromechanical efficiency is about 80%.

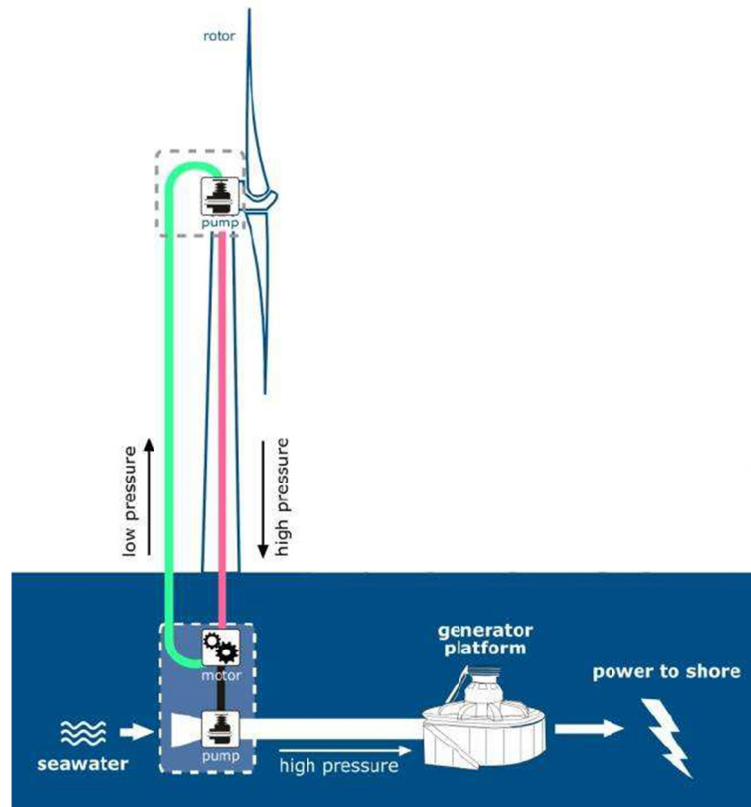


Figure 6. Delft University Offshore Wind Hydraulic Energy Concept

### 2.3 Direct Drive Train (DDT) Wind Turbine

A direct drive train is one that takes the power coming from a motor without any reductions (such as a gearbox). This type of system has been used occasionally in offshore wind turbines, where the expense of repairing a gearbox is more expensive than the gearbox itself. Although DDT offers increased efficiency, reduced noise, and longer lifetimes, all this comes at an expensive price. The main disadvantage of the system is that it needs a special, very expensive motor. The slow, high-torque motor needs to be physically much larger than its faster counterpart, and all this mass must be supported at the top of the turbine tower. Finally, direct-drive mechanisms need a more precise control mechanism. Low-voltage variations on a high-speed motor that are reduced to low rpms can go unnoticed, but in a direct-drive, those variations are directly reflected on the rotational speed.

### 3. Tidal and Wind Hydraulic Energy Transfer (HET) Designs

Unfortunately, none of the European hydraulic wind systems noted above in Section 1.2 have excelled, primarily because the pumps and/or hydraulic generators are complicated, custom machines, and each tower has only one ground generator. In addition, the European HET designs lose a potentially valuable means to increase efficiency, as described below.

JPL/Caltech has recently patented a new means to generate power for tidal energy and wind energy systems (Ref 10, 13) utilizing wind or tides to power a series of ***off-the-shelf radial piston pumps*** (typical efficiency  $\sim 0.95$ ), which send a bio-friendly fluid to a series of ***off-the-shelf, high efficiency, axial piston hydraulic generators***. As the wind speed decreases, the pump efficiency increases, the pressure drop decreases, and the generator performance can be maintained at an optimum rpm by shutting off some of the generators. Other wind generators, both conventional and European hydraulic systems, suffer large losses as the rpms decrease. Wind energy and tidal energy can both be used to turn pumps instead of generators, and the pumped fluid can be transferred remotely to generate electricity. There are numerous advantages to using HET technology which will be explained in the following sections for both tidal energy and wind energy.

#### 3.1 Tidal Hydraulic Energy Transfer

The conventional in-stream tidal turbine shown in Figure 1 is somewhat similar to the wind turbine shown in Figure 5: Turbine blades spin slowly due to the flow of a river, tidal flow, or ocean current. The rotor's rotational speed is increased through a gearbox, which then drives a turbine generator. Each turbine's output is then conditioned and transferred to shore by means of a buried electrical cable. As mentioned in Section 1.1, this submerged electrical design is subject to salt water corrosion of electrical components due to all-too-common leakage of salt-water through its rotating seals. Furthermore, the submerged cable and power conditioning are both expensive and dangerous, and the gears are subject to failure.

The JPL/Caltech HET design for this type of horizontal axis in-stream tidal turbine is shown in Figure 7, with blades and pump rotated  $90^\circ$  for simplicity. For this design (Reference 1), turbine blades spin slowly due to water currents, like the other systems. The rotor's rotational speed is transmitted directly to a commercially available, high-pressure fluid pump, without using any gears. The high-pressure fluid, such as environmentally friendly polyethylene glycol-based synthetic hydraulic fluids (HEPG), is transported in small flexible lines to a shared stainless steel pipe and then to an efficient, onshore hydroelectric power plant. This all-mechanical design is less expensive (Reference 9), more efficient, and eliminates all gears and all submerged electrical component corrosion. A 500-m long, 0.35-m inside diameter pipe at 200 bar (2900 psi) can efficiently deliver 15 MW of hydraulic power to shore.

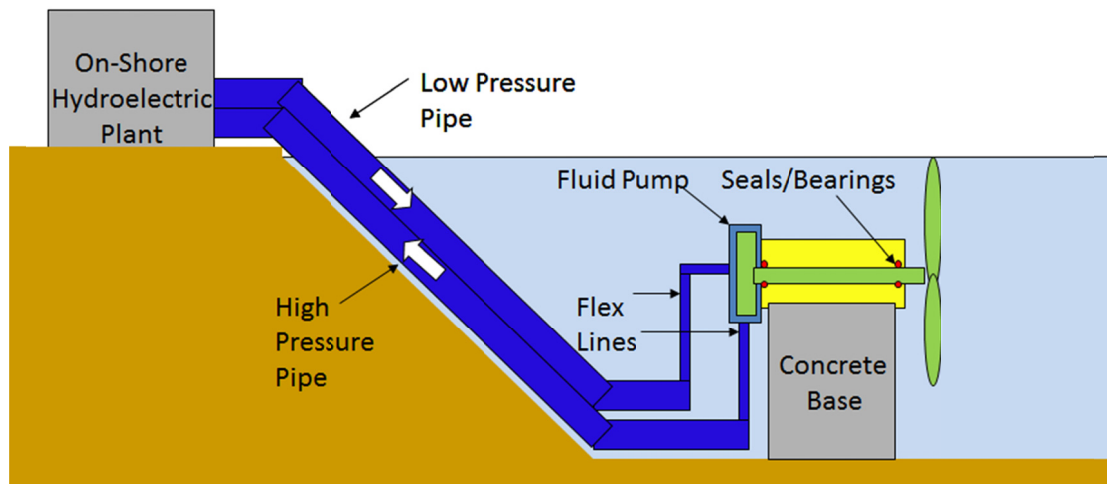


Figure 7. JPL/Caltech Hydraulic Tidal Concept

A series of HET tidal blade units can be combined such that they are all attached to a common high-pressure line that delivers high-pressure fluid to an onshore power plant (Figure 8). A separate line can then deliver low-pressure fluid back to each of the HET tidal blade units.

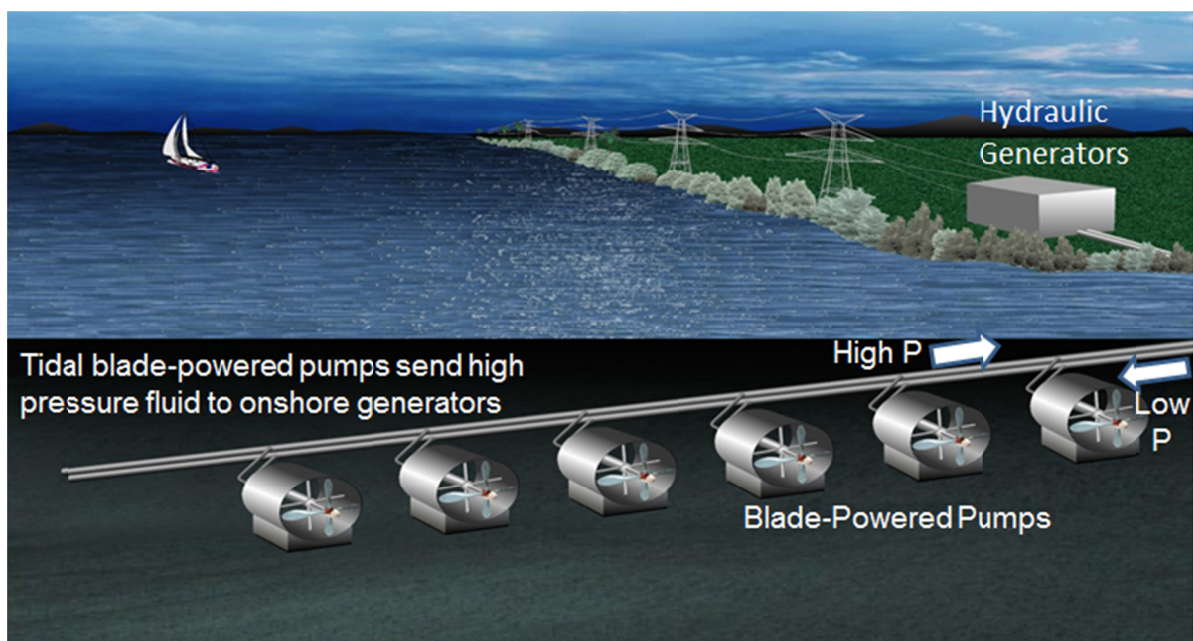


Figure 8. JPL/Caltech Hydraulic Energy Transfer Schematic

For this DOE funded project, a preliminary design has been made for a 15-MW hydraulic tidal power system in Maine's Western Passage tidal area. Both hydraulic systems in Figures 7 and 8 eliminate all gears and submerged electronics, thus greatly improving tidal energy reliability. Caltech has recently been granted patent rights to use this closed cycle hydraulic transfer design for tides, ocean currents, ocean waves, offshore wind, and onshore wind (Reference 10). In a parallel task, the Department of Energy is also funding Sunlight Photonics (FY'11-'12) to design, integrate, and test a 15-kW hydraulic energy transfer tidal

energy system that pumps environmentally friendly, biodegradable fluid to a remote hydroelectric generator (Reference 15). Both the experimental 15-kW system and the analytical design of the 15 MW systems are described later in this report.

### 3.2 Wind Hydraulic Energy Transfer

JPL/Caltech has taken the wind hydraulic energy transfer systems described in Section 1.2 an additional step further. For both offshore and onshore wind energy, the top-mounted pump is used to pump environmentally friendly hydraulic fluid from a series of wind blades directly to a series of generators that are remotely located. For the case of offshore wind, the generators can be located onshore or on a platform offshore (Figure 9).

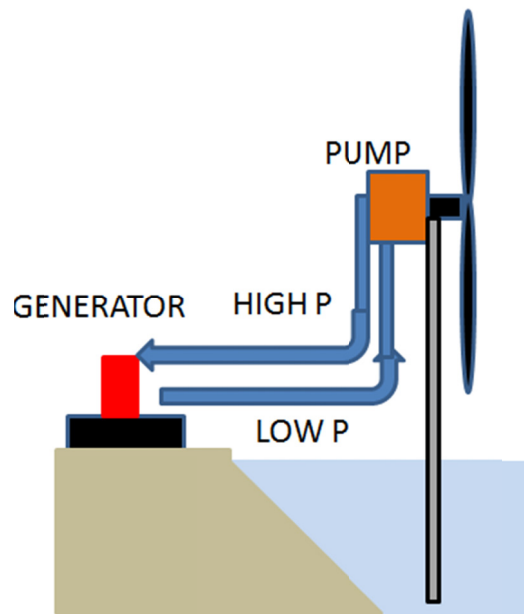


Figure 9. JPL/Caltech Offshore Wind with Hydraulic Energy Transfer

For onshore wind generation, the pumps can connect to a common high-pressure line that goes to a series of remotely located generators. The returning low-pressure fluid then joins a common line to return to the blade pumps. This type of design not only eliminates all troublesome gears, it allows all ground-based generators to be in a common location. As the wind decreases, various hydraulic generators can be shut down to produce a nearly constant high rpm. Also, if there is a failure of one or more generators, they can easily be taken off-line (Figure 10). For offshore wind or for tidal energy, the oil cooling unit can be eliminated, since the pipes themselves will be cooled.

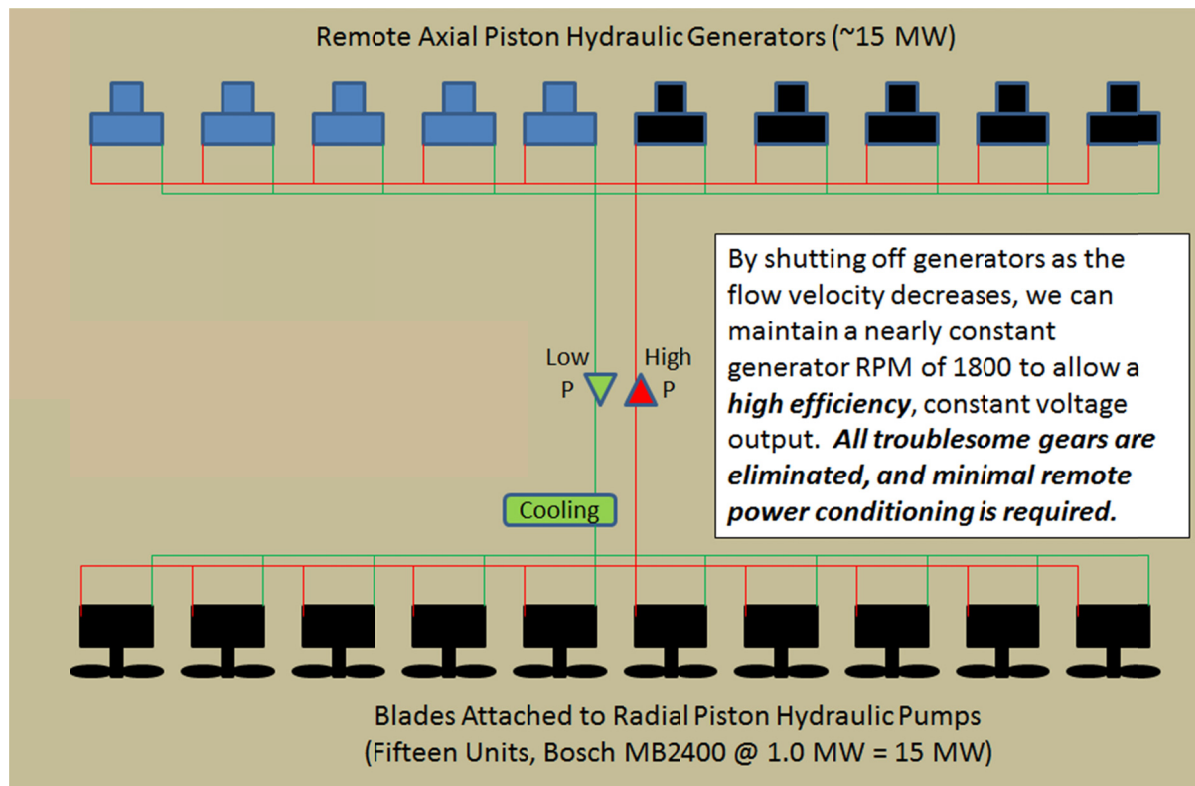


Figure 10. Wind or Tidal Energy Hydraulic Flow Schematic

## 4. Sizing Full Scale Tidal and Wind Hydraulic Transfer Systems

### 4.1 15 MW Hydraulic Tidal System

Preliminary sizing has been performed for a 15-MW tidal energy plant that would be located in Maine's Western Passage from Dog Island to Deer Island Point (Figure 11). We would plan to take 15% of available power, or 15 MW, from the tidal stream in the Western Passage. The blade units we propose to use are the 18-m diameter tidal blades (Figure 2) that have been demonstrated by Atlantis Resources Corporation off the coast of Scotland. Each set of blades are capable of generating 1 MW in a tidal flow of 2.6m/sec, which is the mean maximum tidal flow in the Western Passage. We would use 15 sets of blades that are gravity-placed on the channel floor by means of reinforced concrete foundations. The depth of placement would be at least 30 meters, thus allowing 10 meters of navigable channel above the blades at low tide.

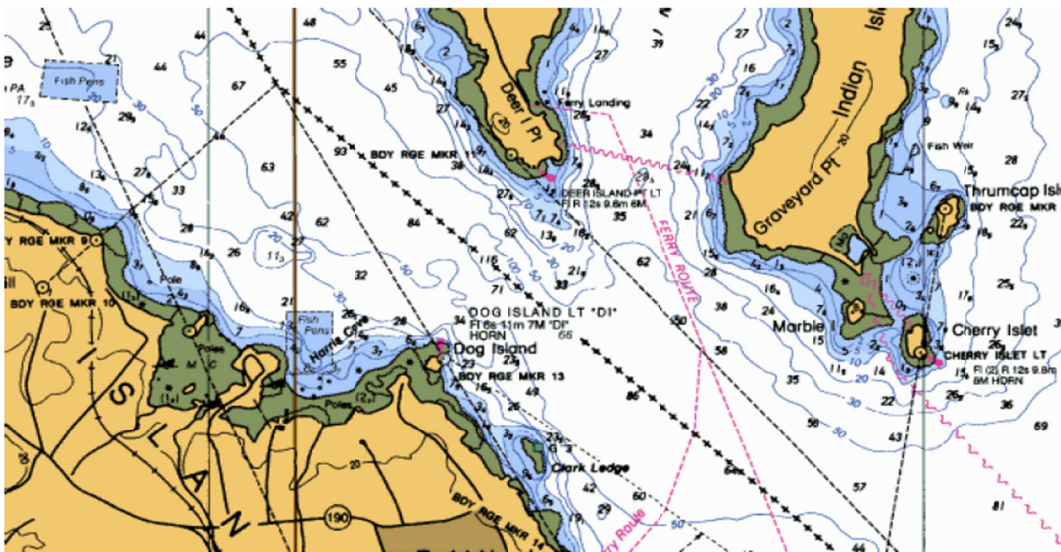


Figure 11. Maine's Western Passage Tidal Area

The corresponding rpm of the Atlantis blades at a tidal flow of 2.6 m/sec is approximately 12 rpm. The rpm and torque corresponds very well with Hagglund's #MB2400-2400 radial piston pump. This pump has no gear reduction, thus avoiding major energy loss and maintenance problems. The MB2400 has a maximum allowable speed of 24 rpm and maximum power output of about 1.55 MW, although these conditions are only meant for short transient operation. There are a variety of onshore hydraulic motors and generators than can generate 1800 rpm of electricity at a combined efficiency of about 90%.

High- and low-pressure hydraulic lines are both attached to the vertical strut of each blade unit. Flexible high-pressure outlet lines and low-pressure inlet lines connect the Hagglund pumps to the permanent lines (Figure 12). The preferred hydraulic fluid is HEPG (polyethylene glycol), which is a non-toxic, environmentally friendly, biodegradable oil that is used as a food additive and is fully miscible with water. Polyethylene glycol has been



shown to have long-term, low toxicity to aquatic organisms with amounts below about 1% (Reference 11).

The average ID of the high-pressure (3000 psi or 207 bar) stainless steel pipe is 35 cm and the average ID of the low-pressure (150 psi or 10.3 bar) reinforced fiberglass pipe is 40 cm. The pipe diameters would be somewhat larger near shore and smaller further away from shore to account for the varying amount of HEPG flow that is carried in the pipes. Total pressure drop in the high-pressure pipe is eight bars, and two bars in the low-pressure pipe, or 5% loss total of the entire flow for the 500-m  $\times$  2 roundtrip length.

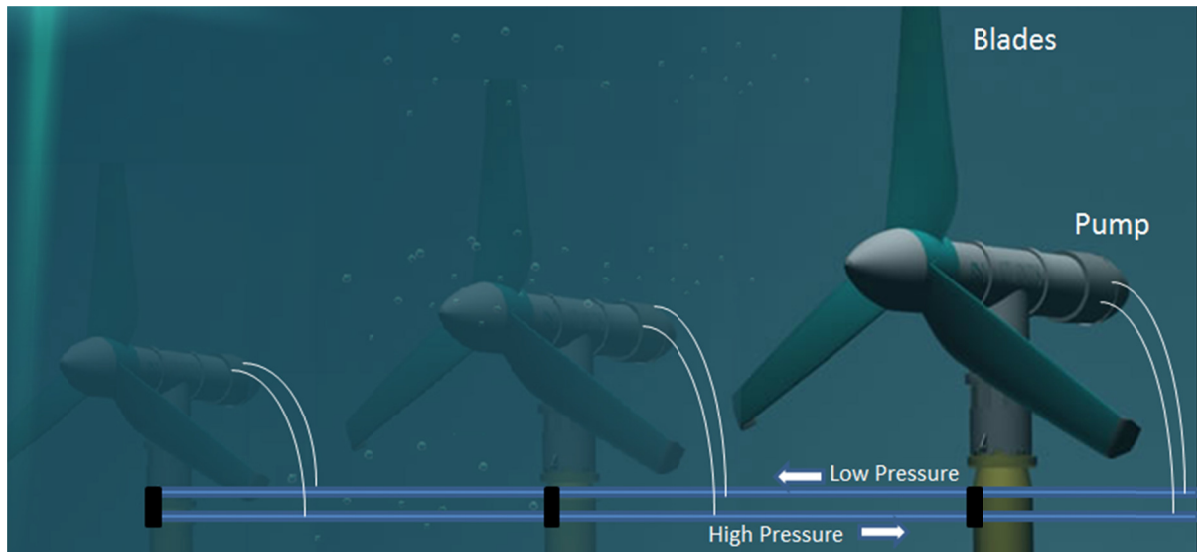


Figure 12. Atlantis Resource 18-m Blades with Hydraulic Energy Transfer

Recent costing of various energy sources for plants entering service in 2016 has been performed by the Energy Information Administration for the Department of Energy (Table 1, Reference 14). Some total system levelized costs include \$0.063/kW-hr (\$63/MW-hr) for advanced cycle natural gas plants, \$0.095 for conventional coal, \$0.140 for coal with carbon sequestration, \$0.097 for conventional wind, and \$0.211 for solar photovoltaic.

Table 1. Estimated Levelized Cost of New Generation Resources, 2016.

| Plant Type                      | Capacity Factor (%) | U.S. Average Levelized Costs (2009 \$/megawatthour) for Plants Entering Service in 2016 |           |                               |                         |                             |
|---------------------------------|---------------------|---|-----------|-------------------------------|-------------------------|-----------------------------|
|                                 |                     | Levelized Capital Cost  | Fixed O&M | Variable O&M (including fuel) | Transmission Investment | Total System Levelized Cost |
| Conventional Coal               | 85                  | 65.3  | 3.9       | 24.3                          | 1.2                     | 94.8                        |
| Advanced Coal                   | 85                  | 74.6  | 7.9       | 25.7                          | 1.2                     | 109.4                       |
| Advanced Coal with CCS          | 85                  | 92.7  | 9.2       | 33.1                          | 1.2                     | 136.2                       |
| Natural Gas-fired               |                     |   |           |                               |                         |                             |
| Conventional Combined Cycle     | 87                  | 17.5  | 1.9       | 45.6                          | 1.2                     | 66.1                        |
| Advanced Combined Cycle         | 87                  | 17.9  | 1.9       | 42.1                          | 1.2                     | 63.1                        |
| Advanced CC with CCS            | 87                  | 34.6  | 3.9       | 49.6                          | 1.2                     | 89.3                        |
| Conventional Combustion Turbine | 30                  | 45.8  | 3.7       | 71.5                          | 3.5                     | 124.5                       |
| Advanced Combustion Turbine     | 30                  | 31.6  | 5.5       | 62.9                          | 3.5                     | 103.5                       |
| Advanced Nuclear                | 90                  | 90.1  | 11.1      | 11.7                          | 1.0                     | 113.9                       |
| Wind                            | 34                  | 83.9  | 9.6       | 0.0                           | 3.5                     | 97.0                        |
| Wind – Offshore                 | 34                  | 209.3   | 28.1      | 0.0                           | 5.9                     | 243.2                       |
| Solar PV <sup>1</sup>           | 25                  | 194.6   | 12.1      | 0.0                           | 4.0                     | 210.7                       |
| Solar Thermal                   | 18                  | 259.4   | 46.6      | 0.0                           | 5.8                     | 311.8                       |
| Geothermal                      | 92                  | 79.3  | 11.9      | 9.5                           | 1.0                     | 101.7                       |
| Biomass                         | 83                  | 55.3  | 13.7      | 42.3                          | 1.3                     | 112.5                       |
| Hydro                           | 52                  | 74.5  | 3.8       | 6.3                           | 1.9                     | 86.4                        |
|                                 |                     |   |           |                               |                         |                             |

<sup>1</sup> Costs are expressed in terms of net AC power available to the grid for the installed capacity.

Source: Energy Information Administration, Annual Energy Outlook 2011, December 2010, DOE/EIA-0383(2010)

Total system levelized costs have also been estimated for the HET tidal energy approach (Table 2). All marine hardware and installation costs have been estimated by Atlantis Research Corp., based on actual fabrication and servicing costs for the Atlantis Research 1-MW tidal turbine. Piping and fluid costs assume stainless steel pipes with HEPG fluid. Hydraulic motor and pump costs have been provided by Bosch-Rexroth Incorporated, and generator costs have been provided by Baldor Motors. Using equations at the bottom of Table 2, the 2012 costs for HET tidal energy are estimated to be about \$0.150/kW-hr, or about \$0.170/kW-hr, based on estimated 2016 costs. This amount is about midway between coal-fired plants with carbon sequestration and energy from solar photovoltaic plants.



Table 2. Cost of Energy (COE) for Hydraulic Tidal Energy

| Component           | Initial Cost for 15 MW Plant (\$K) |          | 5 Yr Maintenance Cost (\$K) |          |
|---------------------|------------------------------------|----------|-----------------------------|----------|
| Ocean Components    |                                    |          |                             |          |
| 18-m Blades/Rotor   |                                    | \$800    |                             | \$400    |
| Nacelle             |                                    | \$2000   |                             | \$1000   |
| Ancillary           |                                    | \$480    |                             | \$240    |
| Pumps               | 300*15=                            | \$4500   |                             | \$2250   |
| Fluid               |                                    | \$600    |                             | \$600    |
| Pre-assembly        |                                    | \$7500   |                             | \$250    |
| Ocean Installation  | 800*15=                            | 12000    | 600*15=                     | \$9000   |
| EPA Approval        |                                    | \$3000   |                             | -----    |
| Pipes               |                                    | \$500    |                             | \$250    |
| Subtotal            |                                    | \$31,380 |                             | \$13,990 |
| Land Components     |                                    |          |                             |          |
| Generator           | 50*15=                             | \$750    |                             | \$375    |
| Hyd Motors          | 50*15=                             | \$750    |                             | \$375    |
| Assembly            |                                    | \$1000   |                             | \$300    |
| Power Conditioning  |                                    | \$1000   |                             | \$500    |
| Grid Connection     |                                    | \$2000   |                             | -----    |
| Outdoor Gen Housing |                                    | \$1,000  |                             | \$200    |
| Subtotal            |                                    | \$6500   |                             | \$1,750  |
| TOTAL               |                                    | \$37,880 |                             | \$15,740 |

$$\text{COE} = [(\text{DR} + \text{IWF}) * \text{ICC} + \text{LRC} + \text{O\&M}] / \text{AEP}$$

DR = 20-year Discount Rate = 0.07

IWF = Insurance, Warranty, and Fees = 0.01

ICC = Initial Installed Capital Cost = \$31,380 K

LRC = Levelized Replacement Costs =  $31,380/20 = \$1569 \text{ K}$

O&M = Levelized Operations and Maintenance Cost =  $(15,740/5)*0.6 = \$1889 \text{ K}$

AEP = Net Annual Energy Production =  $15,000 \text{ KW} * 0.33 * 8760 \text{ hrs} * 0.95 = 41.20 \text{ MW-hrs}$   
(where Average Capacity Factor = 0.33 times Max Power, Availability = 0.95)

**Thus, COE = \$0.149/KW-hr = \$149/MW-hr**

#### Assumptions:

- Major service required every 5 years
- Replacement required at 20 years
- Atlantis Research Corp. 18-m blades with gravity-based system (15 units @ 1 MW max, 0.33 MW aver)
- Bosch pumps and hydraulic motors with Baldor generators
- Sinusoidal tides with peak velocity at 5.1 knots (2.6 m/sec)

## 4.2 Hydraulic Tidal System with ORPC Cross-Flow Blades

An alternative to Atlantis Research Corp.'s 18-m tidal blade design is the ORPC cross-flow turbine system (Figure 4). The ORPC design's turbine rotates in one direction only, regardless of current flow direction, and the generator does not require a gearbox—a major advantage.

In lieu of the ORPC submerged generators, it appears possible to install submerged pumps, similar to those used by the Atlantis Research Corp.'s 18-m blades. This design would still use a  $4 \times 4$  matrix for each tidal generation unit, but the four submerged generators would be replaced with four gearless, Hagglund CM 280 pumps. In all, six  $4 \times 4$  units, one of which is shown in Figure 13, would produce a total of 4 MW peak power.

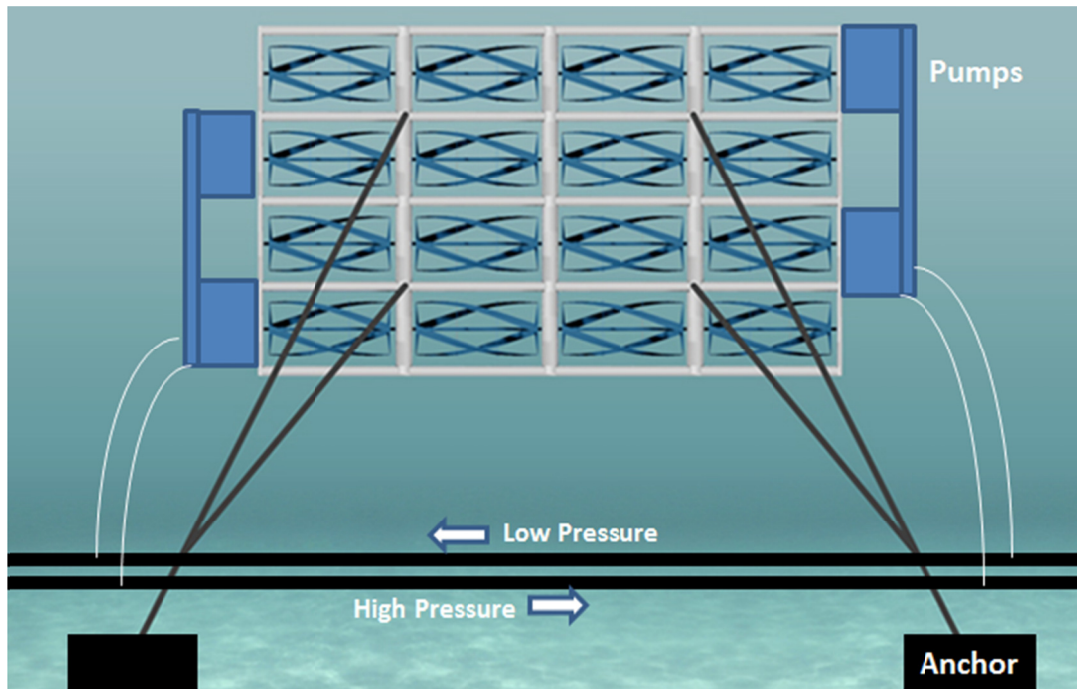


Figure 13. ORPC Cross-flow Blades with Hydraulic Energy Transfer

Total hydraulic conversion cost for the ORPC system has been estimated to be about 50 cents per watt (Table 3), less the cost of the expensive submerged gearless generators, which would be eliminated. Costs assume stainless steel pipes for the high-pressure fluid, FRP pipes for the low-pressure fluid, Bosch-Rexroth axial piston hydraulic motors and radial piston hydraulic pumps, and Baldor generators.

Table 3. Cost of Energy (COE) for ORPC hydraulic Conversion

**Component                      Costs (\$K) for 4 MW ORPC Hydraulic Conversion**

|   |                 |
|---|-----------------|
| Hi Press Steel Pipe<br>(20-cm ID x 300-m) | 75              |
| Low Press FRP Pipe<br>(30-cm ID x 300-m)  | 15              |
| HEPG (10,000 Gal)                         | 200             |
| Hydraulic Motors                          | 300             |
| Generators                                | 200             |
| Radial Piston Pumps    50*24=             | 1200            |
| <b>TOTAL</b>                              | <b>\$1990 K</b> |

For the ORPC hydraulic design, the high-pressure stainless steel pipes would average 20 cm ID, and the low-pressure reinforced fiberglass pipes would average 30 cm ID, resulting in a total system pressure drop loss of 5%. The total amount of non-toxic, environmentally friendly, biodegradable polyethylene glycol (HEPG) would be about 10,000 gallons. Since it is fully miscible with water, if the entire quantity of glycol leaked in a single tidal flow, the total mixed content of glycol with seawater would be about 30 parts per billion, assuming complete mixing.

### 4.3 Preliminary Hydraulic Transfer Wind Energy Sizing

For onshore and offshore wind, a small 15-MW system has been sized, although much larger power systems can be scaled up. We have selected 1.0-MW, 60-m diameter blade sets that rotate at 20 rpm, for a maximum velocity wind of 12 m/sec (27 MPH). Each set of blades is connected to a Bosch-Rexroth/Hagglund radial piston pump (#MB2400-1950).

For this particular example, we assume the generators are located 500 meters away from the wind pump units, and thus an identical 15-MW fluid transfer system as the Atlantis Resource Corp. hydraulic tidal system described in section 3.1. The average ID of the high-pressure (3000 psi or 207 bar) stainless steel pipe is 35 cm and the average ID of the low-pressure (150 psi or 10.3 bar) RFP pipe is 40 cm. total pressure drop is again 5% of the entire flow for the 500-m x 2 roundtrip length. Distances longer than 500 meters would require larger diameters in order to maintain the same 5% total pressure drop loss. These percentage losses are the same as the hydraulic tidal energy system described in Section 4.1, which operates at 12 rpm using a different version of the Hagglund radial piston pump (Hagglund #MB2400-2400).

#### 4.4 Hydraulic Transfer Efficiency for Tidal or Wind Power Systems

The total efficiency of the wind or tidal HET system is as follows for full rated flow velocity:

**Total Efficiency = Pump Effic\*Pressure Effic\*Hydraulic Motor Effic \*Generator Effic**

$$\sim 0.95 * 0.95 * 0.95 * 0.95$$

$$\sim 0.814$$

This total electromechanical efficiency compares well with the Delft University calculation of 80% for an offshore hydraulic wind energy system (Section 2.2, Figure 6)

At 1/3 of the full rated flow speed, the JPL hydraulic pump efficiency increases to about 0.963 (Figure 15) and the pressure drop efficiency increases to at least 0.99. The hydraulic motor and generator efficiency both stay at 0.95 by means of shutting off generators. Thus, total efficiency *increases* to about 0.860 (Figure 14). It should be noted that the efficiency curves of the MB2400-1950 for wind turbines are shifted for the somewhat higher rpms and lower torques corresponding to wind turbines. The resulting total efficiency numbers for both hydraulic wind and tidal energy systems are thus very similar and are shown in Figure 14. This is a large improvement over other wind turbine systems, which suffer significantly *lower* efficiency at low wind speeds. Conventional wind turbine combined gear/electronic efficiencies (Reference 12), excluding power conditioning, vary from about 0.89 (full rated wind velocity), to about 0.5 at 1/2 rated velocity, and to zero (1/3 rated velocity).

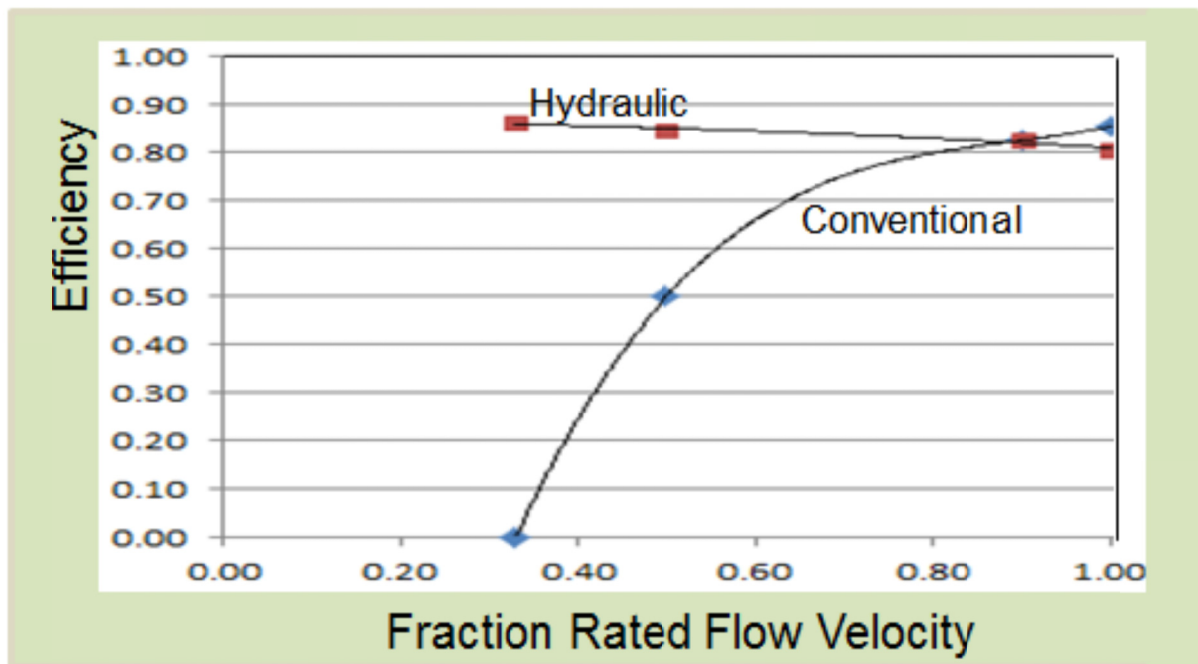


Figure 14. Blade to Grid Total Efficiency for Wind or Tidal Energy

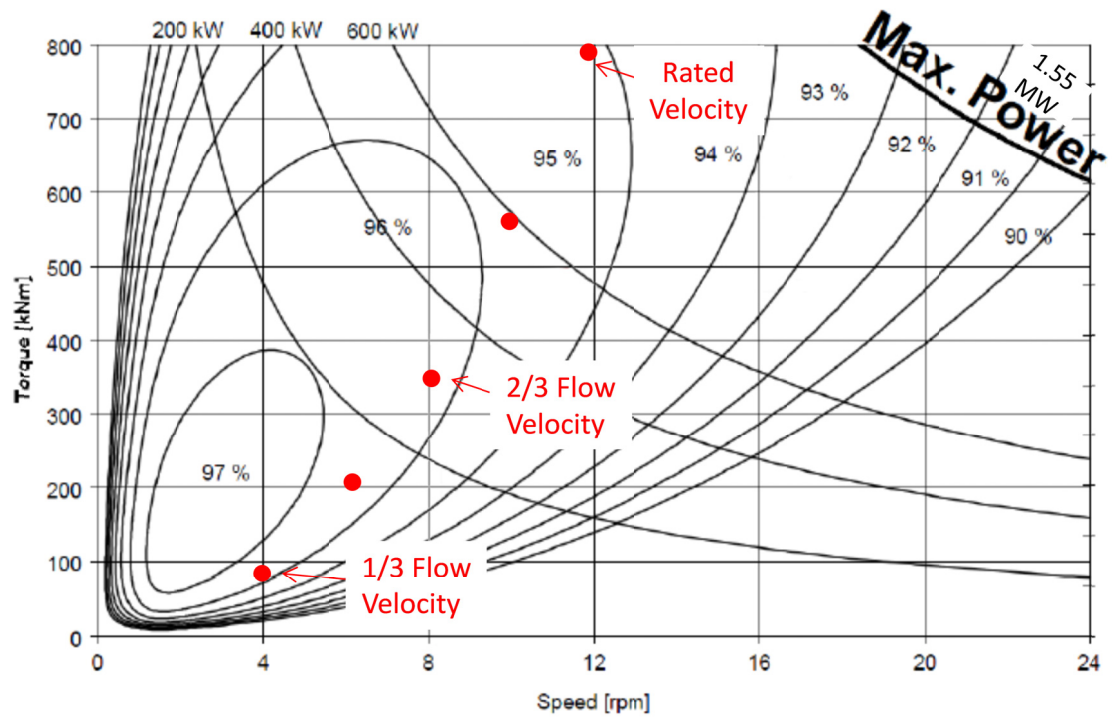


Figure 15. Efficiency Curves for MB 2400 Hydraulic Pump (1 MW)

## 5. Hydraulic Tidal Simulation Test Set Up

In addition to sizing tidal and wind hydraulic transfer systems, another part of this DOE project is to demonstrate a proof-of-principle hydraulic energy transfer design. As shown in Figure 16, a 15 kW AC motor drives a gearbox to simulate the torque and rpm of a 3-m/sec tidal flow on 2-m diameter tidal blades. The gearbox is then connected to a Hagglund pump, which drives an environmentally friendly fluid to a hydraulic generator. It should be noted that the gearbox is only used to simulate the correct tidal blade torque and rpm, and would thus not be in an actual tidal or wind operating hydraulic transfer system. Sunlight Photonics will issue a separate report on this experimental phase, which has successfully integrated and demonstrated all major hardware components.

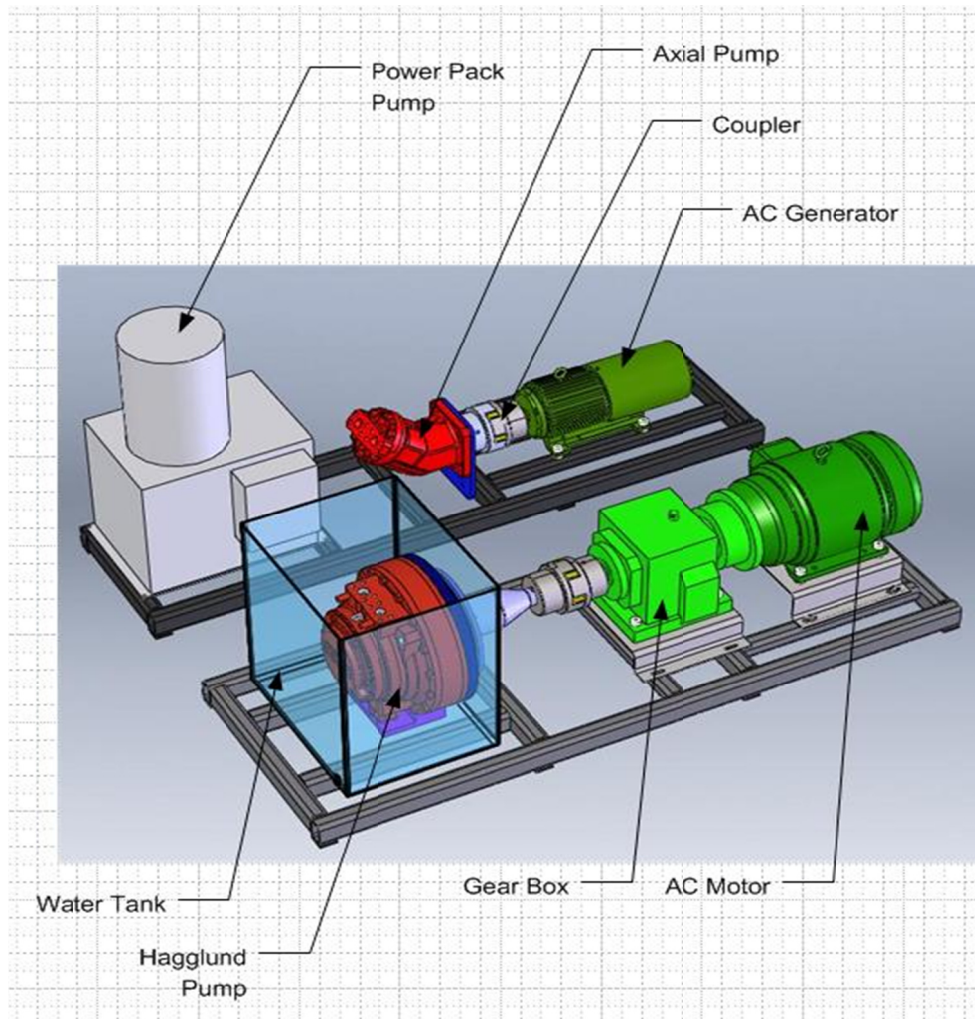


Figure 16. Hydraulic Energy Transfer Test Setup

## 6. Summary and Conclusions

The reliability, maintainability, and efficiency of wind energy and tidal energy systems can be significantly improved by using hydraulic energy transfer designs. In both instances, all failure-prone gears are eliminated, and the electronics are moved to a convenient, more easily maintained, hydraulic power generating station. For tidal energy, all submerged electronics and gears are replaced by off-the-shelf, radial piston pumps, which pump environmentally friendly, water-miscible polyethylene glycol (HEPG) to onshore hydraulic generators. For wind energy, the complex, top-mounted gears and generators are replaced by off-the-shelf, gearless, radial piston pumps, which pump the same HEPG fluid to a central, ground-located series of hydraulic generators, which are much more easily maintained.

By closing off some of the hydraulic generators during slow tidal or wind conditions, it is possible to maintain a nearly constant generator rpm with a high-efficiency power output that requires very little power conditioning. Total wind or tidal energy fractional efficiency actually increases from about 0.81 to about 0.86 when rated velocities decrease to  $1/3$ , while conventional wind and tidal efficiencies decrease to zero at  $1/3$  flow speeds. Similar gearless hydraulic energy transfer designs can be used to harness tidal energy, ocean current energy, river current energy, offshore wind energy, onshore wind energy, and ocean wave energy (Reference 10).

Total cost for hydraulic tidal power production has been estimated to be approximately \$0.15/kW-hr, which is larger than wind power costs, but less than costs for solar power. Total costs to modify the ORPC cross-flow turbines to a hydraulic energy transfer system are approximately \$0.50/watt. The net cost is less after the cost of the expensive multi-pole generators, now used in the ORPC process, is deducted from the total cost of the HET conversion.

## 7. Acronyms and Abbreviations

|      |   |
|------|---|
| COE  | cost of energy                                |
| COTS | commercial-off-the-shelf                      |
| DDT  | direct drive train                            |
| DOE  | Department of Energy                          |
| EMEC | European Marine Energy Centre                 |
| FRP  | Fiberglass reinforced pipe                    |
| HEPG | hydraulic polyethylene glycol                 |
| HET  | hydraulic energy transfer                     |
| ID   | internal diameter                             |
| JPL  | Jet Propulsion Laboratory                     |
| NASA | National Aeronautics and Space Administration |
| ORPC | Ocean Renewable Power Company                 |
| RITE | Roosevelt Island Tidal Energy                 |
| rpm  | revolutions per minute                        |



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# APPENDIX A: GLOBAL MARINE RENEWABLE ENERGY POSTER

5th Annual Global Marine Renewable Energy Conference

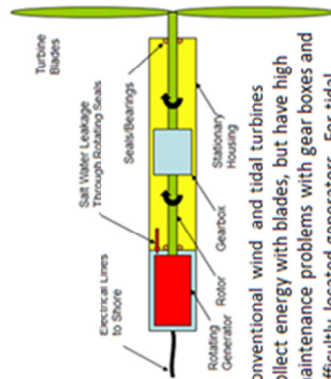
April 24-26, 2012 Washington, DC



## HYDRAULIC ENERGY TRANSFER FOR TIDAL AND WIND ENERGY

Sunlight Photonics, NASA Jet Propulsion Lab Caltech, Atlantis Resources, Maine Maritime Academy TEDEC, Rutgers University

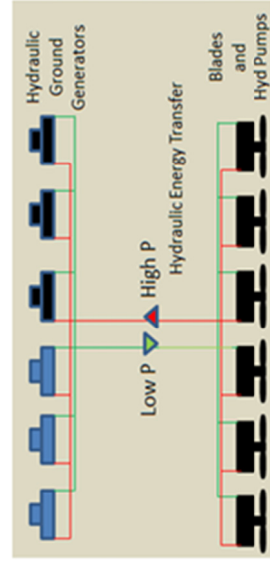
Allan.Bruce@sunlightphotonics.com Jack.A.Jones@jpl.nasa.gov



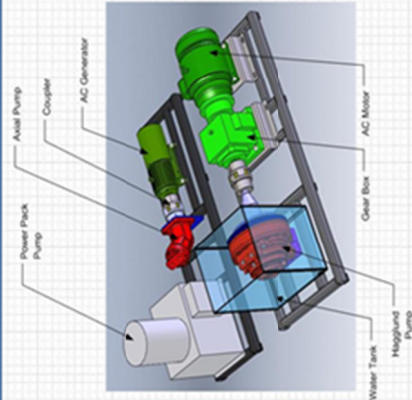
Conventional wind and tidal turbines collect energy with blades, but have high maintenance problems with gear boxes and difficultly located generators. For tidal energy, saltwater leakage often destroys the generators, and for wind turbines the top-mounted generator is difficult to service.



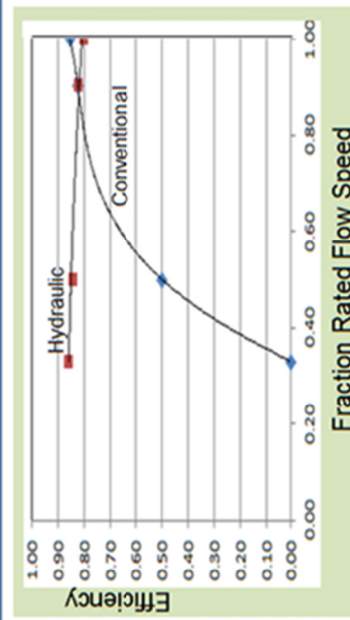
Tidal hydraulic energy transfer uses the blades to turn off-the-shelf pumps, which send a high pressure bio-friendly vegetable oil to shore. The flow is then converted to electricity and the low pressure flow returns to the subsea pumps. All gears and submerged electronics are eliminated.



For wind or tidal energy, axial piston hydraulic generators can be in parallel, such that some units can be shut down, thereby maintaining a high RPM, regardless of wind or tidal flow. Thus the generators maintain high efficiency for all operating conditions (Caltech patent granted and others pending).



Sunlight Photonics and their team have successfully demonstrated a simulated tidal energy radial piston hydraulic generating system at Rutgers University (DOE funded).



At speeds below 90% of rated wind or tidal speeds, the hydraulic energy transfer system total efficiency is much higher than conventional turbines due to the lack of gears and to increased hydraulic efficiency at lower flow speeds, while the generator efficiency remains constant due to high RPM.



### HYDRAULIC WIND ENERGY ADVANTAGES:

- Eliminates generators & costly, low efficiency gears at tower tops
- Provides hydraulic energy transfer with bio-friendly fluids
- Constant generator RPM minimizes power conditioning
- Much higher efficiency than conventional turbines at lower winds
- Can be used for both on-shore and off-shore wind energy

## **APPENDIX B: RENEWABLE ENERGY WORLD CONFERENCE ABSTRACT**

Full paper published by Renewable Energy World Conference, Long Beach, CA, Feb. 2012

### **On-Shore Central Hydraulic Power Generation for Wind and Tidal Energy**

Jack A. Jones<sup>1</sup>, Allan Bruce<sup>2</sup>, Steven Lim<sup>3</sup>, Luke Murray<sup>4</sup>, Richard Armstrong<sup>5</sup>,  
Richard Kimball<sup>6</sup>, Kimberly Cook-Chenault<sup>7</sup>, Sean DeGennaro<sup>8</sup>

1. NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California, 91109, (818) 354-4717, [Jack.A.Jones@jpl.nasa.gov](mailto:Jack.A.Jones@jpl.nasa.gov)
2. Sunlight Photonics, 600 Corporate Court, South Plainfield, New Jersey, 07080, (908) 391-2712, [Allan.Bruce@sunlightphotonics.com](mailto:Allan.Bruce@sunlightphotonics.com)
3. Sunlight Photonics, 600 Corporate Court, South Plainfield, New Jersey, 07080, (831) 713-5822, [Steve.Lim@sunlightphotonics.com](mailto:Steve.Lim@sunlightphotonics.com)
4. Atlantis Resources Corporation, #20-04 Suntec Tower Two 9 Temasek Boulevard, Singapore 038989. Tel +65 6238 6002, [lukemurray@atlantisresourcescorporation.com](mailto:lukemurray@atlantisresourcescorporation.com)
5. Tidal Energy Device Evaluation Center (TEDEC), Maine Maritime Academy, Castine, Maine, 04420, (800) 464-6565 [Rick.Armstrong@mma.edu](mailto:Rick.Armstrong@mma.edu)
6. Tidal Energy Device Evaluation Center (TEDEC), Maine Maritime Academy, Castine, Maine, 04420, (800) 464-6565, [Richard.Kimball@mma.edu](mailto:Richard.Kimball@mma.edu)
7. Rutgers University, Mechanical and Aerospace Engineering Department, 98 Brett Road, New Brunswick, New Jersey, 08854, (732) 445-2248, [kacook@jove.rutgers.edu](mailto:kacook@jove.rutgers.edu)
8. Rutgers University, Graduate Student, Department of Mechanical Engineering, 98 Brett Rd, New Brunswick, NJ, 08854, (973) 459-0689, [sdegennaro387@yahoo.com](mailto:sdegennaro387@yahoo.com)

#### **Abstract**

Tidal energy, offshore wind energy, and onshore wind energy can be converted to electricity at a central ground location by means of converting their respective energies into high-pressure hydraulic flows that are transmitted to a system of generators by high-pressure pipelines. The high-pressure flows are then efficiently converted to electricity by a central power plant, and the low-pressure outlet flow is returned. The Department of Energy (DOE) is presently supporting a project led by Sunlight Photonics to demonstrate a 15 kW tidal hydraulic power generation system in the laboratory and possibly later submerged in the ocean. All gears and submerged electronics are completely eliminated.

A second portion of this DOE project involves sizing and costing a 15 MW tidal energy system for a commercial tidal energy plant. For this task, Atlantis Resources Corporation's 18-m diameter demonstrated tidal blades are rated to operate in a nominal 2.6 m/sec tidal flow to produce approximately one MW per set of tidal blades. Fifteen units would be submerged in a deep tidal area, such as in Maine's Western Passage. All would be connected to a high-pressure (20 MPa, 2900 psi) line that is 35 cm ID. The high-pressure HEPG fluid flow is transported 500-m to on-shore hydraulic generators. HEPG is an environmentally friendly, biodegradable, water-miscible fluid. Hydraulic adaptations to ORPC's cross-flow turbines are also discussed.

For 15 MW of wind energy that is onshore or offshore, a gearless, high efficiency, radial piston pump can replace each set of top-mounted gear-generators. The fluid is then pumped to a central, easily serviceable generator location. Total hydraulic/electrical efficiency is 0.81 at full rated wind or tidal velocities and *increases* to 0.86 at 1/3 rated velocities.